APPLICATION OF AUTOMATIC CODE GENERATION FOR RAPID AND EFFICIENT MOTOR CONTROL DEVELOPMENT

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Requirements dictate fast algorithm execution

- Torque, speed, voltage and fault reaction modes
  - 1000+ Hz fundamental frequency
  - 500+ Hz current regulator bandwidth
  - 10 kHz PWM rates for DC voltage ripple
- 80 – 100 uSec control loops are common
Software Development Process

General Approach

• Responsibilities
  ▪ Systems: Analyze, derive and specify
  ▪ Software: Implement
  ▪ Software/Systems/Validation: Verify

• Time consuming and error prone
  ▪ Requirements formation, implementation and verification are too dispersed
  ▪ Decoupling of domain knowledge from implementation
Automatic Code Generation

Benefits

• Linking of simulation, code development and testing
  ▪ Common in 5 – 10 mSec task rates
  ▪ Improves testability.
• Implementation responsibility transitions to domain experts
• Potential for time savings
  ▪ Faster verification of implementation
  ▪ Production hardware can be used for design and detailed problem solving

Challenges

• Creating and maintaining easily understood environment and models
• Identifying preferred implementations
Develop automatic code generation process for time critical tasks

• Requirements focused
  ▪ To support Automotive SPICE
• Directly apply system expertise to implementation
  ▪ Create path for high level simulation models to software
• Shorten time between design, implementation and verification steps
  ▪ Reduce development time
• Create easy to understand implementations that can be shared among teams
• Closely match hand-code throughput efficiency
Process: Requirements Derivation / Partitioning Phase

High level design

- Verify overall requirements are met
- Establish derived requirements
  - Architecture
  - System partitioning
  - Modes
  - Sample rates / control bandwidths
Process: Implementation Phase

Functional Modules

- Testable requirements
  - Inputs / outputs
  - Functionality
  - Execution rate / order

- Model development
  - Best practices

- Documentation
  - Model / requirements are not sufficient

- Test vectors
  - Simulation
  - Requirements verification
Process: Implementation Phase (Modelling)

Simulation tools offer numerous options for implementation

• Not all approaches will code with equal efficiency
  ▪ Tools have optimization settings
• Consistency of implementation among modules is important for ‘readability’
  ▪ Key for sharing among teams
• Peer review process is important to ensure efficient code
  ▪ Systems: Implementation meets requirements
  ▪ Software: Optimization and problem resolution
    • Detailed review of code
    • Identification of best practices
Process: Implementation Phase (Example 1)

Inefficient Model / Code:

```
real32_T rtb_Gain2;
real32_T rtb_Add2;
rtb_Add2 = Vds_Stat - Vgs_Stat;
T_1_Prim = Vq_Vstat - Vds_Stat;
rtb_Gain2 = 1.0F * Vds_Stat;
switch (Sector_Num) {
  case 3:
    T_1_Prim = rtb_Gain2;
    break;
  case 2:
    T_1_Prim = rtb_Add2;
    break;
  case 4:
    T_1_Prim = rtb_Gain3;
    break;
  case 5:
    T_1_Prim = rtb_Add2;
    break;
  case 1:
    break;
}
```

Efficient Model / Code:

```
switch (Sector_Num) {
  case 3:
    T_1_Prim = 2.0F * Vds_Stat;
    break;
  case 2:
    T_1_Prim = Vds_Stat - Vgs_Stat;
    break;
  case 4:
    T_1_Prim = 2.0F * Vds_Stat;
    break;
  case 5:
    T_1_Prim = Vds_Stat - Vgs_Stat;
    break;
  case 1:
    T_1_Prim = Vgs_Stat - Vds_Stat;
    break;
  default:
    T_1_Prim = Vgs_Stat - Vds_Stat;
    break;
}
```
Inefficient Embedded MATLAB code:

```matlab
floor_index = uint32(unfloor_index);
```

Generated code:

```c
/* */
/* 'S3':1:46 */
tmp = unfloor_index;
if ((unfloor_index < 8.388608E+6F) && (unfloor_index > -8.388608E+6F)) {
    tmp = (unfloor_index < 0.0F) ? ceilf(unfloor_index - 0.5F) : floorf
        (unfloor_index + 0.5F);
}

floor_index = (uint32_T)tmp;
```
Process: Implementation Phase (Example 2)

Inefficient Embedded MATLAB code:

```
45
46 - floor_index = uint32(unfloor_index);
47
```

Generated code:

```
/*
 * <S3>:1:46 */

tmp = unfloor_index;
if ((unfloor_index < 8.388608E+6F) & (unfloor_index > -8.388608E+6F)) {
    tmp = (unfloor_index < 0.0F) ? ceilf(unfloor_index - 0.5F) : floorf
        (unfloor_index + 0.5F);
}

floor_index = (uint32_T)tmp;
```
Process: Implementation Phase (Example 2)

Efficient Embedded MATLAB Code:

Hand-coded CustomFunction.h:
```c
#ifndef CustomFunction_H
#define CustomFunction_H

#include "rtwtypes.h"

#define SingleToInteger32(u) ((int32_T)u)
```

Generated code:
```c
/* '<S3>:1:46' */
floor_index = SingleToInteger32(unfloor_index);
```
Process: Verification Phase

Test to verify requirements are met

- Module test vectors
  - Verify functionality
    - Inputs / internal variables / outputs

- Full model test vectors
  - Simulation environment
  - Hardware in the loop
    - Correct compiler
    - Simulate virtual load in processor or test bench
Evaluation of Process

Verified auto generated software was dynamometer tested to evaluate performance

- Comparison was made to mature hand-code
- Equivalent motor control functionality
- Slight penalty in 100 uSec task throughput
  - 1.54 uSec

<table>
<thead>
<tr>
<th>Task / Module</th>
<th>Throughput (uSec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model</td>
</tr>
<tr>
<td>Current Magnitude and Phase Process</td>
<td>1.42</td>
</tr>
<tr>
<td>ABC to dq0 Frame Transformation</td>
<td>0.76</td>
</tr>
<tr>
<td>Resolver Harmonic Learn</td>
<td>0.48</td>
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<tr>
<td>Angle Position Determination</td>
<td>0.93</td>
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<tr>
<td>PI-Current Regulator</td>
<td>7.62</td>
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<tr>
<td>Torque Mode</td>
<td>4.82</td>
</tr>
<tr>
<td>dq0 Rotating to Stationary Frame Transformation</td>
<td>0.94</td>
</tr>
<tr>
<td>Complete 100 uSec Task</td>
<td>65.37</td>
</tr>
</tbody>
</table>
Summary

Structured automatic code generation can be applied to time critical tasks

• A process is required to ensure efficient implementations
• New roles
  ▪ Software: responsible for auto-coding environment, determining best practices, peer reviewing implementations and detailed problem solving
  ▪ System: responsible for forming requirements, creating implementations that demonstrably meet requirements (test vectors) and following identified best practices
• Requirements and models are not sufficient to document implementation
• Automatic code generation should be viewed as a tool to link simulation, implementation and verification testing
  ▪ Concurrent activities speed the software development process
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